theoretical (Quinten et al., *Surf. Sci.* **172**:557 (1986); Yang et al., *J. Chem. Phys.* **103**:869 (1995)) treatments of gold nanoparticle aggregates. However, the *magnitude* of the shift is small compared to that previously observed for suspensions of oligonucleotide-linked gold nanoparticle networks, which show $\lambda_{max} > 570$ nm (see previous examples). This suggests that many more linked nanoparticles --- perhaps hundreds or thousands --- are required to produce the dramatic color change from red to blue observed for gold nanoparticle-based oligonucleotide probes. (Storhoff et al., *J. Am. Chem. Soc.* **120**:1959 (1998); Storhoff et al., *J. Cluster Sci.* **8**:179 (1997); Elghanian et al., *Science* **277**:1078 (1997); Mirkin et al., *Nature* **382**:607 (1996).). Surface plasmon shifts for aggregated gold nanoparticles have been shown to be highly dependent on interparticle distance (Quinten et al., *Surf. Sci.* **172**:557 (1986); Storhoff et al., *J. Am. Chem. Soc.*, in press), and the large distances provided by oligonucleotide linkers (8.2 nm for this system)) significantly reduce the progressive effect of nanoparticle aggregation on the gold surface plasmon band.

The dissociation properties of the assembled nanoparticle multilayers were highly dependent upon the number of layers. When the multilayer-coated substrates were suspended in buffer solution and the temperature raised above the T_m of the linking oligonucleotides (53°C), the nanoparticles dissociated into solution, leaving behind a colorless glass surface. Increasing or decreasing the pH (>11 or <3) or decreasing the salt concentration of the buffer suspension (below ~0.01 M NaCl) also dissociated the nanoparticles by dehybridizing the linking DNA. The multilayer assembly was fully reversible, and nanoparticles could be hybridized to, and dehybridized from, the glass substrates (*e.g.* three cycles were demonstrated with no detectable irreversible nanoparticle binding).

Significantly, while all of the surface bound nanoparticle assemblies dissociated above the T_m of the linking oligonucleotides, the sharpness of these transitions depended on the size of the supported aggregate, Figure 39D-F. Surprisingly, the dissociation of the first nanoparticle layer from the substrate exhibited a transition (Figure 39D, FWHM of the first derivative = 5 °C) that was sharper than that of the same oligonucleotides without

nanoparticles in solution, Figure 39C. As more nanoparticle layers were hybridized to the substrate, the melting transition of the oligonucleotide-linked nanoparticles became successively sharper (Figure 39E-F, FWHM of the first derivative = 3 °C), until it matched that of the large nanoparticle network assemblies found in solution. (Gittins et al., *Adv. Mater.* **11**:737 (1999); Brust et al., *Langmuir* **14**:5425 (1998)). These experiments confirm that more than two nanoparticles and multiple DNA interconnects are required to obtain the optimally sharp melting curves. They also show that the optical changes in this system are completely decoupled from the melting properties (*i.e.,* small aggregates can give sharp transitions but still not change color).

Example 21: Electrical Properties of Gold Nanoparticle Assemblies

Electron transport through DNA has been one of the most intensely debated subjects in chemistry over the past five years. (Kelley et al., *Science* **283**:375-381 (1999); Turro et al., *JBIC* **3**:201-209 (1998); Lewis et al., *JBIC* **3**:215-221 (1998); Ratner, M. *Nature* **397**:480-481 (1999); Okahata et al., *J. Am. Chem. Soc.* **120**:6165-6166 (1998)) Some claim that DNA is able to efficiently transport electrons, while others believe it to be an insulator.

In a seemingly disparate field of study, a great deal of effort has been devoted to examining the electrical properties of nanoparticle-based materials. (Terrill et al., *J. Am. Chem. Soc.* **117**:12537-12548 (1995); Brust et al., *Adv. Mater.* **7**:795-797 (1995); Bethell et al., *J. Electroanal. Chem.* **409**:137-143 (1996); Musick et al., *Chem. Mater.* **9**:1499-1501 (1997); Brust et al., *Langmuir* **14**:5425-5429 (1998); Collier et al., *Science* **277**:1978-1981 (1997)). Indeed, many groups have explored ways to assemble nanoparticles into two- and three-dimensional networks and have investigated the electronic properties of such structures. However, virtually nothing is known about the electrical properties of nanoparticle-based materials linked with DNA.

For the first time, in this study, the electrical properties of gold nanoparticle assemblies, formed with different length DNA interconnects have been examined. As shown below, these hybrid inorganic assemblies behave as semiconductors, regardless of

oligonucleotide particle interconnect length over a 24 to 72 nucleotide range. The results reported herein indicate that DNA interconnects can be used as chemically specific scaffolding materials for metallic nanoparticles without forming insulating barriers between them and thereby destroying their electrical properties. These results point towards new ways such hybrid assemblies can be exploited as electronic materials.

At the heart of this issue is the following question: Can nanoparticles assembled by DNA still conduct electricity or will the DNA interconnects, which are heavily loaded on each particle, (Mucic, R. C. *Synthetically Programmable Nanoparticle Assembly Using DNA,* Thesis Ph. D., Northwestern University (1999)) act as insulating shells? The conductivities of these materials as a function of temperature, oligonucleotide length, and relative humidity were examined. The DNA-linked nanoparticle structures were characterized by field emission scanning electron microscopy (FE-SEM), synchrotron small angle x-ray scattering (SAXS) experiments, thermal denaturation profiles, and UV-vis spectroscopy.

In a typical experiment (see Figure 40), citrate-stabilized 13 nm gold nanoparticles were modified with 3' and 5' alkanethiol-capped 12-mer oligonucleotides **1** (3' SH $(CH_2)_3O(PO^{2-})$O-ATGCTCAACTCT 5' [SEQ ID NO:59]) and **2** (5' SH $(CH_2)_6O(PO^{2-})$O-CGCATTCAGGAT 3' [SEQ ID NO:50]) as described in Examples 1 and 3. DNA strands with lengths of 24, 48, or 72 bases (**3** (5'TACGAGTTGAGAATCCTGAATGCG3' [SEQ ID NO:60]), **4** (5'TACGAGTTGAGACCGTTAAGACGAGGCAATC-ATGCAATCCTGAATGCG 3'[SEQ ID NO:61]), and **5** (5'TACGAGTTGAGACCGTTAAGACGAGGCAATCATGCATATATTGGACGCTTT ACGGACAACATCCTGAATGCG3'[SEQ ID NO:62]) were used as linkers. Fillers **6** (3'GGCAATTCTGCTCCGTTAGTACGT5'[SEQ ID NO:63]) and **7** (3'GGCAATTCTGCTCCGTTAGTACGTATATAACCTGCGAAATGCCTGTTG5' [SEQ ID NO:64]) were used with the 48 and 72 base linkers. The DNA-modified nanoparticles and DNA linkers and fillers were stored in 0.3 M NaCl, 10 mM phosphate (pH 7) buffer (referred as to 0.3 M PBS) prior to use. To construct nanoparticle assemblies, **1**-modified